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CONTROL OF MIXING
BY
MEMS BASED DISTRIBUTED FUEL INJECTORS

Final Report

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ABSTRACT

In this paper, we propose to use micro injectors to control mixing of flow for combustion enhancement. The principle and development of the micro injectors are described. Ejection of droplets (8 μm in diameter) from the micro injectors has been detected with a pulse train of 53 mA current, 1 kHz frequency, and 1/30 duty cycle. In parallel, an air jet experiment has been performed to control the shedding frequency of the air jet with perpendicularly injected droplets by utilizing a commercial inkjet printhead (HP 51604A) as the source of droplets. The results demonstrated the ability for the injected droplets to change the flow's characteristic frequency from the natural shedding one to the forcing (injection) one.

Fig. 1 Combustion Improvement by Forcing

INTRODUCTION

Combustion efficiency depends on the mixing rate of reactants. The reactants in a shear flow are first entrained by large vortical structure (Brown and Roshko. 1974) and then mixed by fine scale eddies. The entrainment can be greatly enhanced by either actively (Ho and Huang, 1982) or passively (Ho and Gutmark, 1987) control the evolution of the large vortices. The effectiveness of controlling large scale vortical structures in increasing the combustion efficiency also has been experimentally demonstrated (Shadow et al., 1987). Fig. 1 shows that the combustion effeciency in a dump combustor is greatly enhanced by forcing the jet flow. However, how to improve the

small scale mixing and how to reduce the evaporation time of liquid fuel are still challenges in combustion research.

In this work, we apply micromachining technologies of Microelectromechanical Systems (MEMS) to develop micro

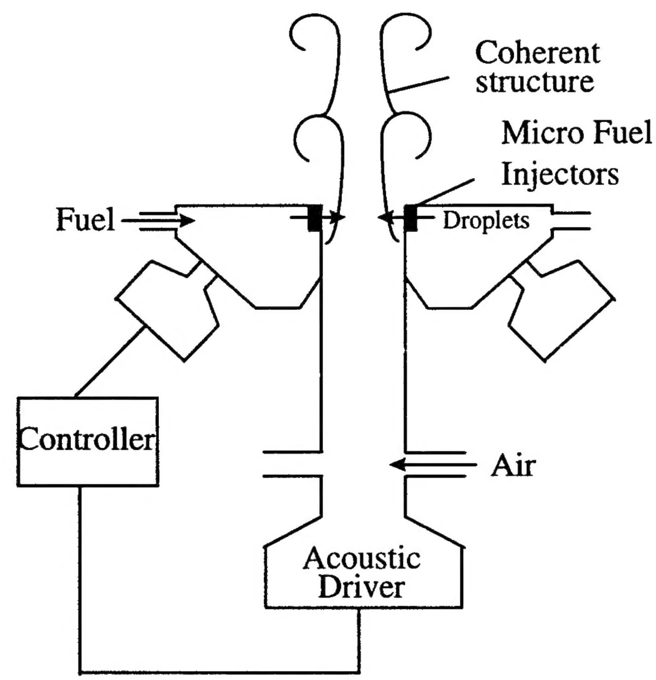


Fig. 2 Air Jet with Micro Injectors. (Envisioned for Dump Combustor)

injectors. The droplet size will be in the order of the micro scale of turbulence so that fine scale mixing can be much improved. The evaporation time is significantly reduced due to the small fuel droplet. Furthermore, the collection of the micro injectors distributed around the nozzle of a dump combustor (Fig. 2) can still provide spatial coherent perturbations for controlling the large vortices. Two types of coherent structures, spanwise and streamwise vortices, can be influenced by imposing subharmonics of the most unstable instability frequency to enhance mixing. In other words, the micromachining technology offers a new type of injectors which can significantly improve the combustor performance.

In the second section of this paper, the design, fabrication, and testing of micro injectors are described. Before the packaging of micro injectors is completed, the control of air jet with micro drops is tested with commercial inkjet printhead as a simulated injector. The result is reported in the third section.

MICRO INJECTORS

In this section, the basic principle, fabrication process, and testing of the micro injectors are reported.

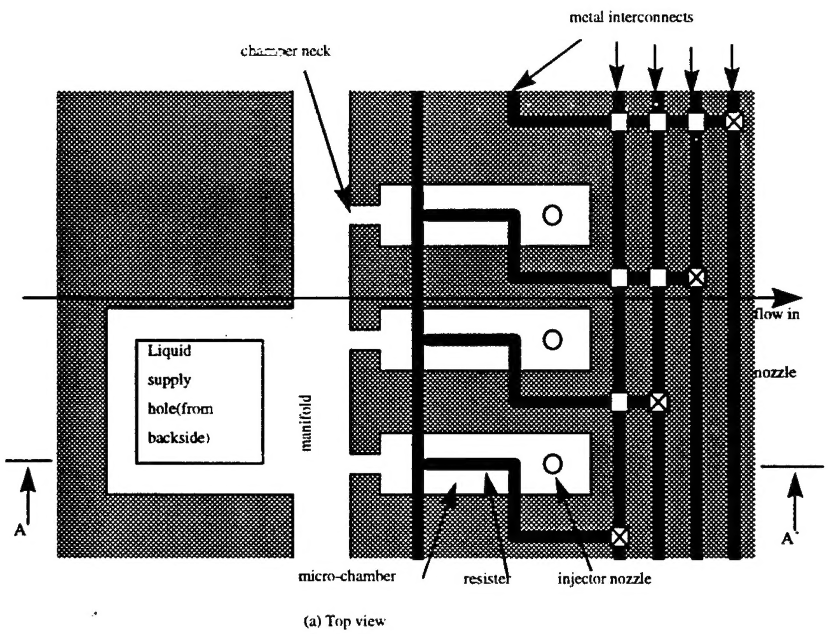


Fig. 3 Design of Micro Injectors.

Design and Principle

The design of the micro injector is schematically shown in Fig. 3 & 4. The device, made with a silicon wafer, is based on surface micromachining for micro-chambers and injector nozzles, combined with bulk micromachining to open the entrance for liquid filling from the wafer backside. The heaters of the micro injectors are made by phosphorous doped polysilicon and

have a width of 8 μm, length of 48 μm, and thickness of 0.3 μm. The resistance of the heater is measured 1.5 K ohms. Liquid, supplied to the manifold from the wafer backside, fills the micro-chambers by capillary force.

The principle of the micro injectors is similar to that of the ink-jet printheads. When the resister in the chamber is heated by pulsed electric current, the liquid boils and is pushed outward through the injection nozzle by the expanding bubble. The bubble collapses when power stops, then new liquid refills the chamber. The chamber neck provides flow resistance to constrain the back-flow during injection and the overshoot during chamber refilling. The time constant of the heating and cooling process is expected to be in the order of micro seconds, and thus the repetition of shooting can be fast (~ kHz), as manifested by commercial inkjet printhead (Allen and Meyer, 1985).

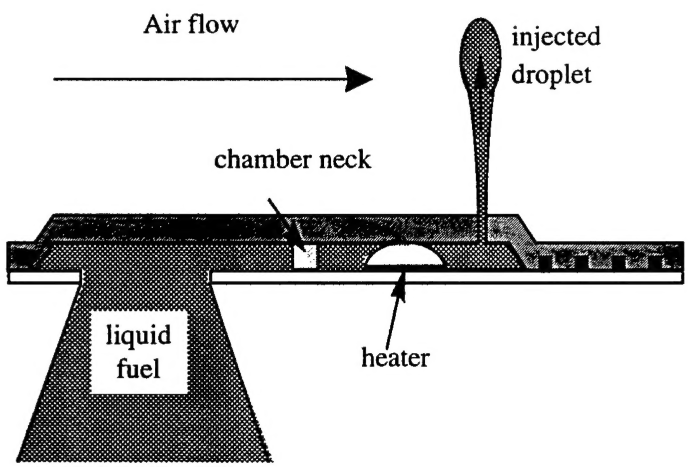


Fig. 4 Principle of Micro Injectors.

Compared with the commercial printhead (HP 51604A), the current device has higher spatial and temporal resolution, flatter surface, and no need of wafer bonding, which are all desired for the given application of flow mixing. In the application of the fine scale mixing enhancement, the size of the droplets is important and needs to be kept in the order of micrometers in diameter. Therefore, the size of the micro nozzles have been designed to be at the micrometer range. Besides, the space between each chambers has been designed as smaller than 100 μm to ensure the spatial resolution of micro injector can resolve spanwise vortices (9 mm in wave length for

our air jet). In the present design, the nozzle diameter and the space between the micro injectors are as small as 8 μm and 80 μm respectively, much smaller than those of commercial inkjet printhead (60 μm and 300 μm, respectively, for HP 51604A, for example).

To increase the influence to streamwise vortices for better mixing, the shooting frequency of the micro injectors need to be higher than the shedding frequency of the air jet for enough temporal resolution. The reported thermal cycle of HP 51604A printhead is smaller than 24 microseconds (Allen and Meyer, 1985). Based on the fact that a time constant below 24 μs (including heating and cooling time) is fast enough to modify the shedding frequency of the air jet at the wind speed of 15 m/s (the shedding frequency of our air jet is around 1 kHz at this wind speed), the micro injector under development smaller than the inkjet printhead is expected to satisfy the frequency requirement.

Fabrication

Fig. 5 shows the process flow to fabricate the micro injectors. The fabrication starts by depositing 0.1 μm low pressure chemical vapor deposition (LPCVD) silicon nitride for substrate passivation. Then a 0.3 μm LPCVD doped polysilicon layer is deposited and patterned to form heaters and interconnection lines. After the deposition of 0.2 μm silicon nitride for heater protection, a 2 μm PSG (phosphosilicate glass) layer is deposited and patterned to define the micro-chamber. Another LPCVD polysilicon (2 μm) is deposited and patterned, followed by the deposition of another LPCVD silicon nitride passivation layer (Fig. 5a). After RIE (reactive ion etching) opens etching windows, a KOH anisotropic wet etching is performed to open the liquid entrance on the back-side and the V-grooves (for wafer breaking) on the front-side (Fig 5b). The PSG layer is removed by HF wet etching after the protective silicon nitride at the nozzle is removed by RIE (Fig 5c). Finally an aluminum bonding pad is evaporated and patterned. In this process, all of the structures are formed on a single silicon wafer monolithically. The materials for micro-injectors can endure temperatures of several hundred degrees (°C), which is essential for combustion applications.

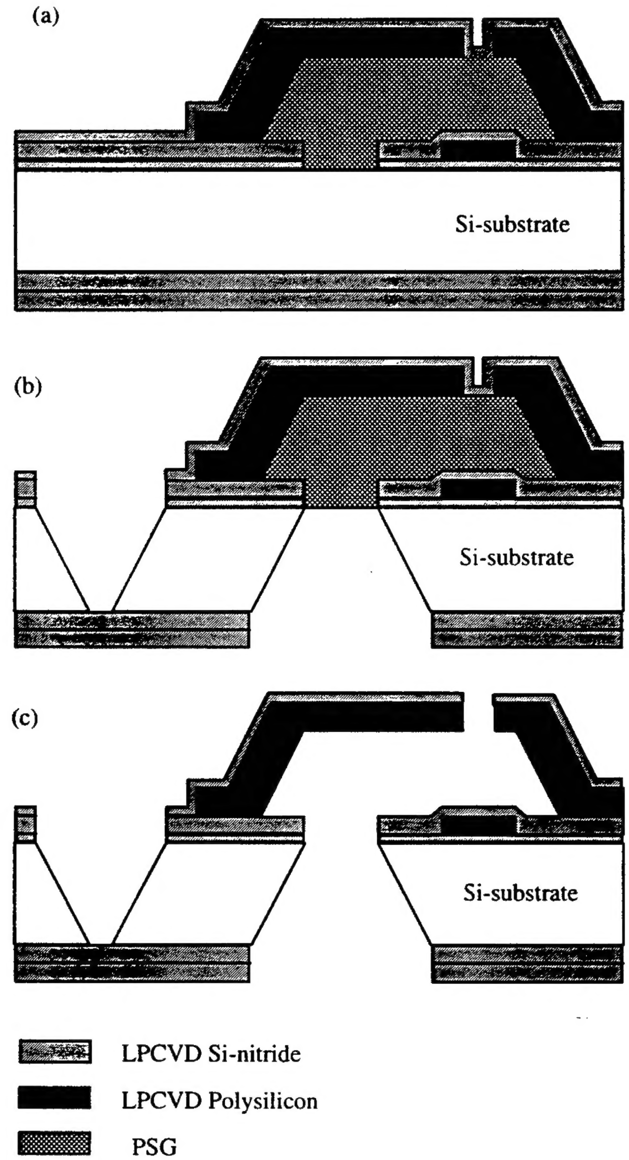
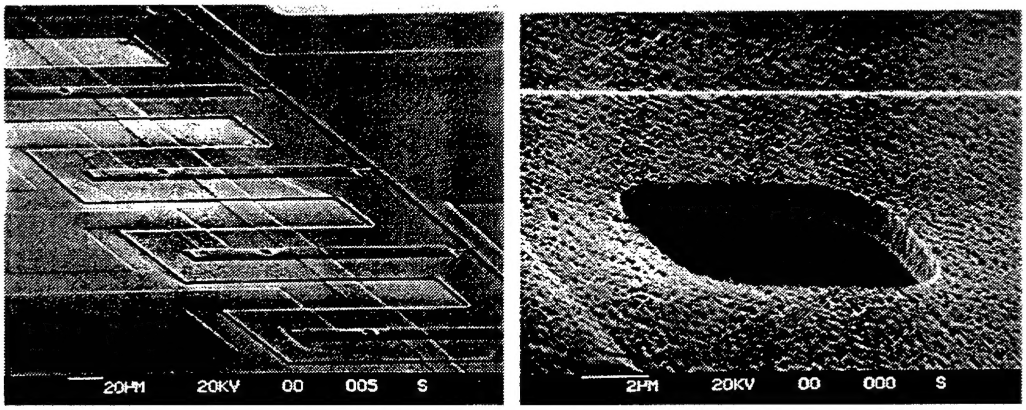


Fig. 5 Fabrication Process

Results and testing

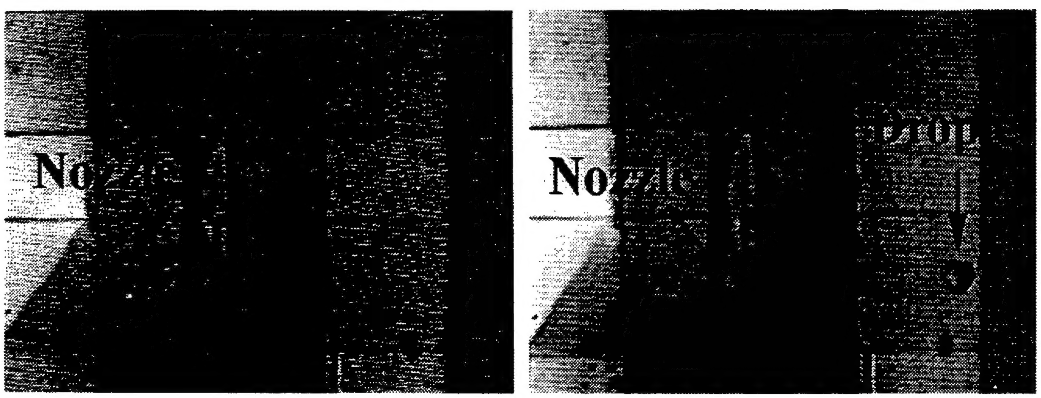
The SEM (scanning electron micrograph) pictures of the micro injectors are shown in Fig. 6. Fig. 6a shows an array of the micro injectors. The micro chamber is 100 μm long, 20 μm wide, and 2 μm deep and the space between each channel is about 80 μm. The diameter of the micro nozzle is about 8 μm, and a close up of the nozzle is shown in Fig. 6b.



a. An array of micro injector

b. A micro nozzle

Fig. 6 SEM Pictures of the Injectors



a. Before injection

b. An injected droplet shown

Fig. 7 Top View of a Micro Injector. (An Injected micro drop 8 μm in diameter, is shown in picture b.)

In a testing of the channel clearance, liquid successfully passed through the channel when brought through the liquid supply hole on the back side. Deionized (DI) water was used for the experiment. When pulses of DC voltage 40 V were applied across the heater of 1.5 kΩ, bubbles were observed to escape through the nozzle. Successful droplet ejection has been observed when a 80 V pulse train was applied at 1 kHz to the heaters with 1/30 duty cycle. In this observation,

Sony CMA-D2 CCD (charge coupled device) camera is used to grab images. Fig. 7 shows two video frames in one of which an ejected micro droplet is captured. The picture shows that the size of the droplet is of the same scale of the diameter of the micro nozzle.

TEST OF FORCING EFFECT

With the air jet facility shown in Fig. 8, we demonstrate that the vortical structures in the jet can be manipulated by modulating the injecting frequency within the instability band of the jet flow.

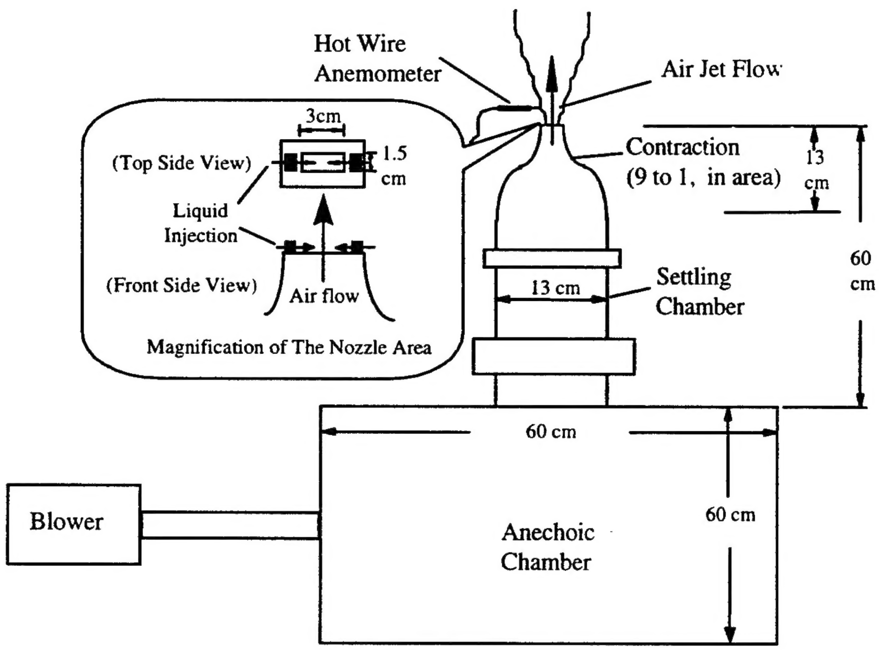


Fig. 8 Flow Testing Facility.

Air coming from the blower goes to a settling chamber and exhausts into the atmosphere through the rectangular jet. The dimensions of the rectangular jet is 3 cm × 1.5 cm with a nine to one contraction in area. Two commercial printheads (HP 51604A) with eleven nozzles each are placed face to face around the rectangular nozzle. They inject droplets into the air flow in the transverse direction without phase lag between each nozzle. The injecting speed is around 10 m/s according to the data from HP (Allen and Meyer, 1985). The commercial inkjet printhead is

used while the packaging of the micro injectors and the development of the phase driving circuit are underway.

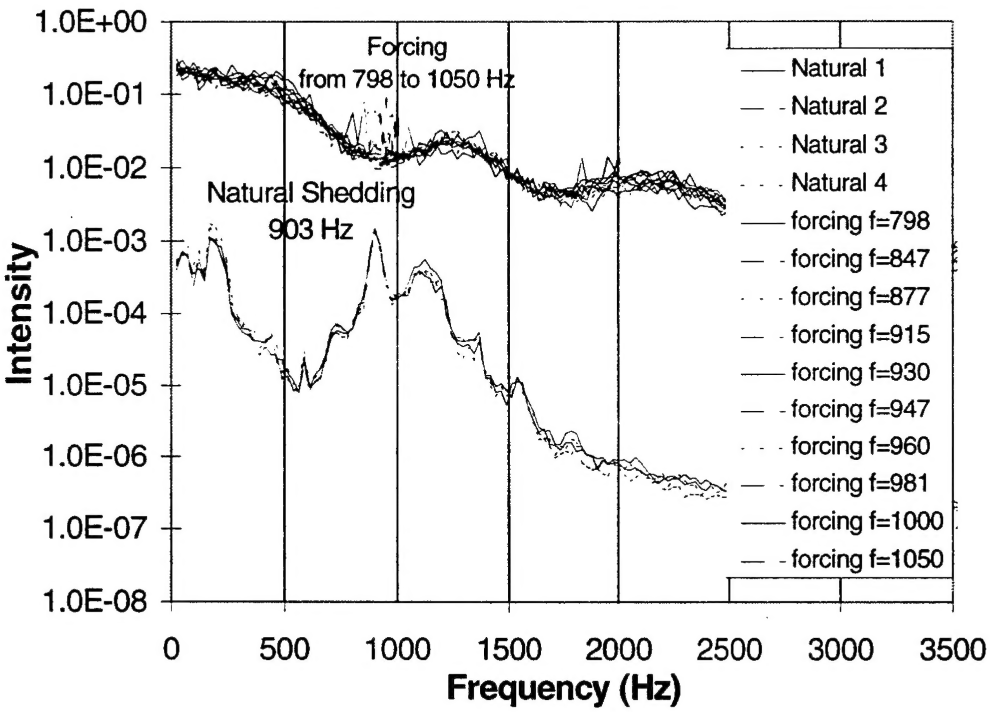


Fig. 9 Result of Flow Frequency Control by Forcing with Droplets (Using Inkjet Printhead)

A hot-wire anemometer for the velocity measurement is located close to the periphery of the square nozzle and 1 cm above the exit (at the region of air jet flow mixes with ambient air). In the experiment, the time-averaged velocity of air was measured to be 12 m/s. The shear layer instability frequency (shedding frequency) was determined from the spectrum readout. The lower lines in the Fig. 7 shows the spectra for the vortices of the air jet without droplet shooting. The peak value of the spectra appears at 903 Hz for four lower lines, which is the shedding (natural) frequency for the air jet. The natural frequency for air jet is measured 4 times, two before the droplets shooting (lines nature 1 & 2) and two after the droplets finish shooting (lines nature 3 & 4). They show highly consistent.

During the period of droplets shooting, we investigate the signal from hot wire anemometer to make sure the droplets did not hit the wire frequently enough to affect the shedding signal (at worse one hitting pulse in ten cycles of shedding). When the forcing (injecting) frequency changes from 798 Hz to 1050 Hz, the peaks in the measured velocity spectra follow the driving frequency (Fig. 9). There is no effect on the shedding frequency for applying forcing outside the effective frequency band. This result indicates the vortex passage frequency is controlled by the injected droplet within a band from 798 to 1050 Hz. To implement the injectors for spanwise vortices and fine scale mixing applications, micro injectors with higher spatial resolution and smaller nozzle size need to be used.

SUMMARY

A micro injector has been fabricated. Injection of droplets (order of 10 μm) was observed when electric pulses were applied to the heater,. The micro injectors are developed to control mixing of fuel inside combustion chamber. With the commercial inkjet printer head, we have demonstrated that the global flow can be controlled by the injected droplets.

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